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THE EFFECT OF VARIATIONS IN CONTROL SYSTEM DYNAMICS UPON TRACKING PERFORMANCE

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THE EFFECT OF VARIATIONS IN CONTROL SYSTEM DYNAMICS UPON TRACKING PERFORMANCE

INTRODUCTION

In any attempt to study the performance of man in a man-machine system the usual procedure has been to vary certain features of the system in such a manner that the effects of a given variation can be inferred from the operator's performance. Such an approach is predicated upon the assumption that those variables not investigated can be held in a constant state across trials and conditions. When the task posed to the operator is a compensatory tracking task the number of variables which, theoretically, could influence his performance is of such a magnitude that it would be prohibitive to attempt to investigate the effect of a systematic manipulation of their values in a single or limited number of experiments. Consequently, it is the intent in the present investigations to study only those variables which, when taken as a class, constitute the dynamic characteristics of a tracking system. A large portion of the research in this area has revolved about the problems of control-display (C/D) ratio and system lag (C/D time delay).

The C/D ratio is traditionally defined as the ratio of a control input to the amount of display movement or system output. Although there are a number of ways of producing variations in this ratio the body of research having the greatest bearing on the present investigation employed an alteration analogous to a "mechanical" or gear-type variation. With this technique the amplitude (and frequency content when using a cam arrangement) of the disturbing function is held constant, and the amplitude of the control

movement required to null the displayed error is made the independent variable. The results[3] of the various investigations have, in general, pointed up to the fact that there is an optimal C/D ratio for each tracking situation but the value of the ratio itself is influenced by the values of the other parameters which make up the system. In short, then, the optimal C/D ratio is not an invariant but a value, the effectiveness of which is specific to the situation obtained. In addition, there is some evidence[2] that efficiency of tracking performance increases and then decreases as the rate of display movement increases with a given control input. This would imply that there are display rates both too slow and too fast to be tracked efficiently relative to rates falling between the extremes.

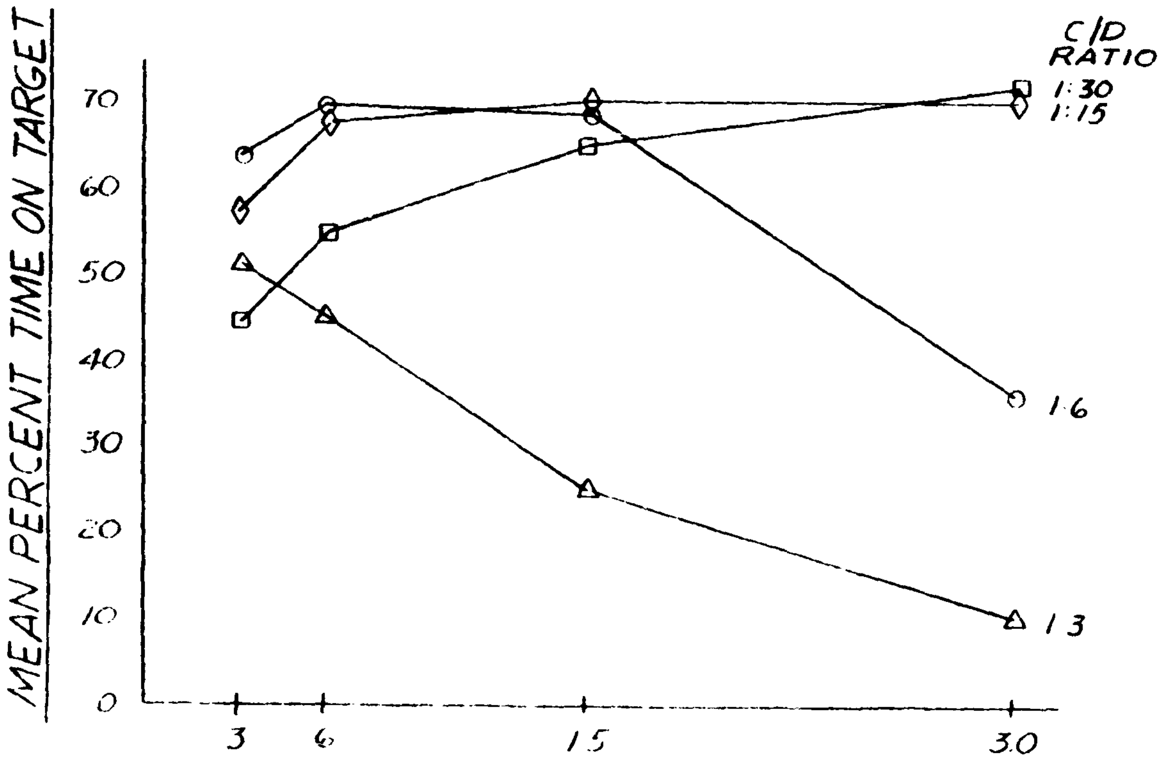
In the area of control-display time delay there exists a limited number of papers pertaining to the parameter inherent in almost all control systems. The effect has been shown to be important in a variety of situations, both in the laboratory and operationally. In short, there appears to be at least four different types of system lags which have been investigated in various experimental settings: transmission-type, exponential delay, sigmoid exponential and oscillatory transient. With a transmission-type lag there is a certain period of time following a control input during which the system does not respond at all, but when response does occur it is instantaneous. On the other hand a system with an exponential delay between control input and system output responds immediately, but as an exponential function of time rather than instantaneously. This type of delay is defined as the time required for the system or display member to attain 63% of its ultimate value following a step input. As has been pointed out[5] the concept of time

constants is meaningless unless this or some such value is specified. The sigmoid exponential is defined in the same terms as the exponential delay except that a system with such an input-output time relationship attains its final value as a sigmoid function of time. The study of the fourth type of lag, the oscillatory transient, has become of increasing importance with the advent of high performance and, to some extent, unstable systems. In fact it is this transient itself which affects the stability of a system. It is difficult to measure or define the lag of a system with such a response, but the usual procedure is to describe the system output "(a) in terms of the period of oscillation, and (b) in terms of the time to damp the successive amplitude of the oscillations...."[5(p.10)] Although the lag is present it is difficult to describe in the same straightforward terms possible with the three preceding types of system response.

As for the results of the investigations in this area, excluding those pertaining to <u>oscillatory transients</u> which are both limited in quantity and difficult to obtain, it has been generally demonstrated that increasing the <u>time delay</u> produces a decrement in performance. This generalization has withstood a variety of experimental conditions and situations but, notwithstanding, it appears reasonable to assume that for a given C/D ratio there exists a time delay which is too short to be tracked efficiently or, stated differently, the system responds too quickly to a control input to be controlled efficiently.

Rockway[6], reasoning along these lines, conducted an investigation designed to demonstrate the presence of interaction effects between C/D ratio and

exponential time dealy. His results, presented in part in Figure 1, indicate that for small values of C/D ratio (the smaller the ratio the larger the value of display change resulting from a given control input) an increase within limits in C/D time delay produces an increase in tracking performance. It would appear that for ratios of these magnitudes an increase in the system lag serves to "slow down" or "de-sensitize" the system's response to some range of values that are more compatible with the operator's response capacity. On the other hand an increase in the time delays for C/D ratios of larger values results in a system the responsiveness of which is too slow to be controlled efficiently. These results would imply that the interaction of various time delays and C/D ratios produces a continuum, and that this continuum might be expressed in terms of the rate of movement of the display index following a step input of the control. If this is true it follows that an increase in time delay for some C/D ratios would result in an increase in tracking performance, and for others a decrease would serve the same purpose. Conversely, for some values of C/D time delay, an increase in the C/D ratio would aid system controllability and, for others, a decrease in the ratio would serve the same end result. The veridity of such an analysis is obviously coupled to the restraint that it be conducted within the limits posed by the response capabilities of the operator and the transmission capacity of the system. Although intuitive, it appears that the preceding observations, couched in terms of the rate of movement of the display element following a control input, are justifiable when Rockway's data are replotted as depicted in Figure 2[4]. An examination of



C/D TIME DELAY (SEC)

Figure 1
MEAN PERCENT TIME-ON-TARGET SCORES FOR EACH COMBINATION OF C/D RATIO AND TIME DELAY FROM ROCKWAY, M.R., WADC TECHNICAL REPORT 54-618

Figure 2

REPLOT OF ROCKWAY'S DATA OF FIG. 1

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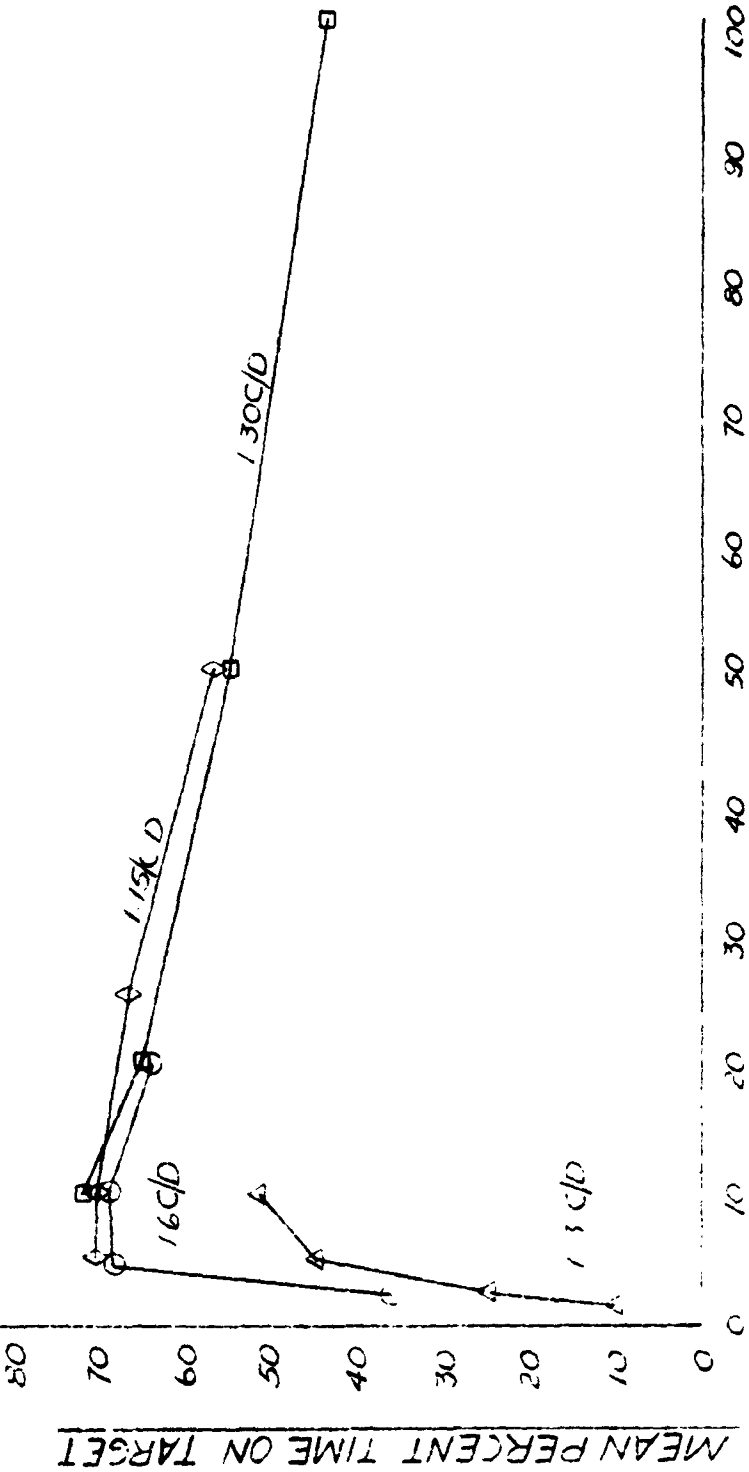
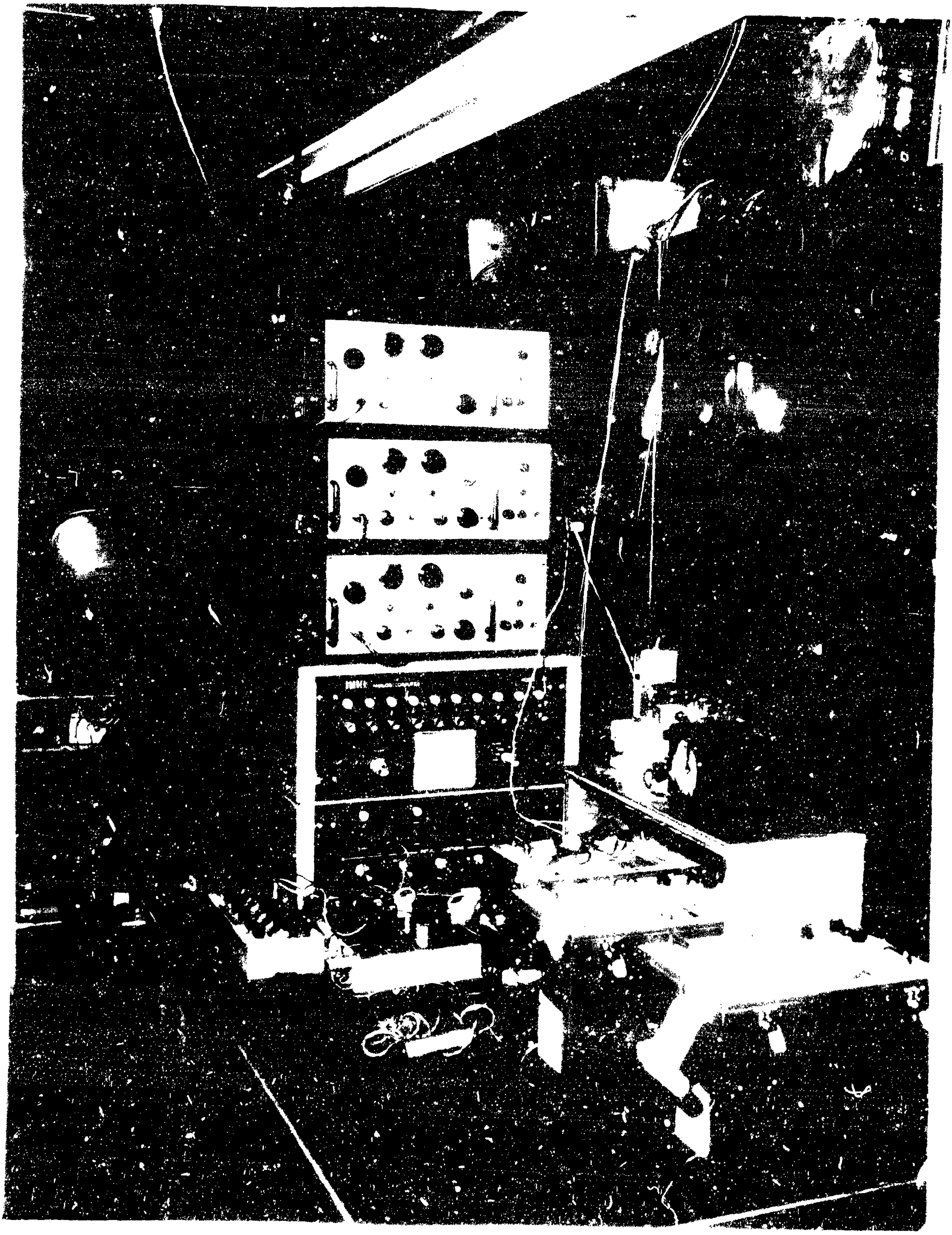
TECHNICAL REPORT (PRELIMINARY DRAFT) APRIL 1958



RATE OF MOVEMENT IN UNITS/SECOND
ASSUMING A UNITARY STEP INPUT TO THE CONTROL

the data plotted in this manner suggests the possibility of explaining the operator's performance in terms of one function rather than two, as represented by the original data. It may be that this function is the immediacy with which the results of an operator's control movements are made available to him through the display. The curves show that performance efficiency increased and then decreased as the rate of movement of the display was increased. However, in addition to being a function of system lag this rate is also determined by the C/D ratio and the equation which describes the time-displacement relationship. As such, the time required for the display to attain some rate which is perceptible to the operator may be varied by changing this equation and, consequently, the slope of the curve which describes it. Increasing the slope of the time-displacement function and, by so doing, decreasing the time at which the display member attains a rate of motion which is perceptible to the operator should serve to provide more immediate knowledge of control movement results. This observation is not intended to imply that a decrease in the time to attain a perceptible rate will facilitate performance in any combination of C/D ratio and system lag, but the investigation of such a manipulation within prescribed limits should provide additional insight into the effect of these variables upon tracking performance.

The two studies to be reported were designed primarily to demonstrate the validity of the hypothesis that the function determining operator performance in a tracking situation is the rate of movement of the display element in response to a control input rather than the value of the C/D ratio or system lag as such. For some combinations of C/D ratio and system



lag an increase in the rate of movement of the display index will provide more immediate knowledge concerning the results of control movements with a concurrent facilitation of performance.

METHOD

APPARATUS:

This investigation was conducted in two parts, the first experiment being concerned with the compensatory tracking of a display along the vertical dimension of a cathode-ray tube (CRT), and the second experiment consisted of the tracking of the angular rotation of the same display as it rotated about its axis. The equipment, subjects and procedure for the two experiments were identical.

The tracking display consisted of a 3-inch fluorescent winged-symbol on the face of a 17-inch CRT situated approximately 28 inches from the subject with the center of the scope located at eye-level for all subjects.

The tracking control consisted of a spring-centered displacement-type control mounted on the right arm-rest of a seat similar to that encountered in commercial passenger-carrying aircraft. The control and arm-rest were adjusted in such a manner that the control could be manipulated comfortably with articulated movements of the S's wrist. For Expt. I fore and aft movements produced a vertical excursion of the display symbol of ±5½ inches, and in Expt. II lateral motion of the control produced an angular rotation of the symbol of ±45°. Maximum deflection of the control in the fore and aft dimension produced a total travel at the top of the stick of 4-3/4 inches and an angular displacement from the vertical of ±30°. Right-left movements

of the control, operating about a different fulcrum, produced a travel of 1¼ inches at the top of the stick and an angular displacement of ±10°. The arrangement of the control and display is illustrated in Figure 3.

The exponential time functions utilized in both experiments were generated on a Donner Model 3000 analog computer. Variations in the C/D ratio were obtained by adjustments of two potentiometers in the control output and feedback circuits.

The error of disturbing function was generated by a single potentiometer attached to a spring-loaded cam follower in such a manner that it followed the contours of a synchronous motor-driven cam rotating at 1 rpm. The contour of the cam was derived from the graphic representation of NACA[1] data on gust structure and "continuous" rough air.

In Expt. I the maximum "pitch" excursion of the display produced by the cam was ±4 inches, and in Expt. II the maximum "roll" excursion was ±30°. When controlling for "pitch" the S's task was to keep the display symbol aligned with a thin, black line spaced horizontally in the center of the CRT. When controlling for "roll" in the second experiment he was instructed to null any angular excursions of the display in order to maintain it in a horizontal position.

The S's performance was recorded on a Model 151 single-channel Sanborn recorder. The signal recorded was the voltage difference which existed at any time between the S's control output and the cam output. In this way it was possible to measure both the amplitude and direction of the error induced by the S's control movements.

In Expt. I an error above the reference index was recorded as a positive signal and below, as a negative signal. When controlling for roll in Expt. II a clockwise rotation of the display was recorded as a positive signal and a counter-clockwise deflection as a negative signal. In addition, a Standard Electric clock was used to record trial length and rest interval.

SUBJECTS:

The Ss consisted of 24 male adults whose ages ranged from 21 to 33 years. All of the Ss were naive to the extent that they had never served as subjects in a tracking experiment. Each S served in each of 24 conditions for each of the two experiments.

CONDITIONS:

The design of the two experiments is presented in Table 1. The two parameters of C/D ratio and system lag were each investigated at six different levels, and a third parameter of exponential function was varied at two levels. The selection of C/D ratios and lags was dictated to a great extent by the hypothesis.

Since it has been hypothesized that the determining factor in tracking performance is the rate of display movement, the product of the interaction between C/D ratio and system lag and not the value of the ratio or lag as such, it was necessary to choose values which would give equivalent average rates. If the operator responds only to rate of display movement, then performance on a given rate should be equivalent regardless of how obtained.

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TABLE 1

THE DESIGN OF THE EXPERIMENTS

	CONSTANT LAG (L_K)												CONSTANT DISPLACEMENT (D_K)											
	D_1		D_2		D_3		D_4		D_5		D_6		L_1		L_2		L_3		L_4		L_5		L_6	
S's	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu	Fs	Fu
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1	24	2	23	3	22	4	21	5	20	6	19	7	18	8	17	9	16	10	15	11	14	12	13
2	24	23	1	22	2	21	3	20	4	19	5	18	6	17	7	16	8	15	9	14	10	13	11	12
3	2	1	3	24	4	23	5	22	6	21	7	20	8	19	9	18	10	17	11	16	12	15	13	14
4	23	22	24	21	1	20	2	19	3	18	4	17	5	16	6	15	7	14	8	13	9	12	10	11
5	3	2	4	1	5	24	6	23	7	22	8	21	9	20	10	19	11	18	12	17	13	16	14	15
6	22	21	23	20	24	19	1	18	2	17	3	16	4	15	5	14	6	13	7	12	8	11	9	10
⋮																								
24	13	12	14	11	15	10	16	9	17	8	18	7	19	6	20	5	21	4	22	3	23	2	24	1

TABLE 2

TIME-DELAY AND C/D RATIO VALUES OF EXPERIMENT I

FUNC-TION	CONSTANT C/D (1:1) LAG #1 2 sec.	LAG #2 1 sec.	LAG #3 .667 sec	LAG #4 .5 sec.	LAG #5 .25 sec.	LAG #6 .167 sec	CONSTANT LAG (1 sec.) C/D #1 1:.5	C/D #2 1:1	C/D #3 1:1.5	C/D #4 1:2	C/D #5 1:4	C/D #6 1:6
Fs	1"/2 sec	1"/1 sec	1"/.667	1"/.5 sec	1"/.25	1"/.167	.5"/1 sec	1"/1 sec	1.5"/1 sec	2"/1 sec	4"/1 sec	6"/1 sec
Fu	1"/2 sec	1"/1 sec	1"/.667	1"/.5 sec	1"/.25	1"/.167	.5"/1 sec	1"/1 sec	1.5"/1 sec	2"/1 sec	4"/1 sec	6"/1 sec

TABLE 3

TIME-DELAY AND C/D RATIO VALUES OF EXPERIMENT II

FUNC-TION	CONSTANT C/D (.5:1) LAG #1 1 sec.	LAG #2 .5 sec.	LAG #3 .33 sec.	LAG #4 .20 sec	LAG #5 .143 sec	LAG #6 .111 sec	CONSTANT LAG (1 sec.) C/D #1 .5:1	C/D #2 .5:2	C/D #3 .5:3	C/D #4 .5:5	C/D #5 .5:7	C/D #6 .5:9
Fs	1°/1 sec	1°/.5 sec	1°/.33 sec	1°/.20 sec	1°/.143	1°/.111	1°/1 sec	2°/1 sec	3°/1 sec	5°/1 sec	7°/1 sec	9°/1 sec
Fu	1°/1 sec	1°/.5 sec	1°/.33 sec	1°/.20 sec	1°/.143	1°/.111	1°/1 sec	2°/1 sec	3°/1 sec	5°/1 sec	7°/1 sec	9°/1 sec

EXPERIMENT I:

The values of C/D ratio and system lag utilized in Expt. I are presented in Table 2. Each of the six time delays was combined with a constant C/D ratio of 1:1, and each of the six C/D ratios was combined with a constant time lag of 1 sec. A C/D ratio of 1:1 should be interpreted as 1° of control input produced a displacement of 1 inch of the display symbol, 2° produced a 2-inch change, 3° produced a 3-inch change, and so on. For each combination of ratio and lag the response of the display to a step input of the control was varied in two ways, as a negatively accelerated time exponential and as a positively accelerated time exponential. An examination of Table 2 indicates that each lag and ratio combination was expressed as a rate of movement in inches/sec. It will be noticed that the rate obtained with a constant C/D of 1:1 and a variable time-lag of 2 secs. was equivalent to the rate obtained with a variable C/D of 1:.5 and a constant time lag of 1 sec. Reading from left to right it is apparent that there were six conditions of rate of display movement, but each rate was obtained in two ways. The notations S_F and U_F in Table 2 should be read as stable function and unstable function respectively. Stable functions were represented by display responses which accelerated negatively with time, and unstable functions by responses which accelerated positively with time.

With the largest ratio of 1:.5 it required 8° of control movement to compensate for the maximum display deflection of 4 inches produced by the problem cam, whereas the smallest ratio of 1:6 required less than 1° of control input to completely null out the maximum displacement.

EXPERIMENT II:

The conditions of Expt. II are given in Table 3. As in Expt. I there were twenty-four conditions consisting of a systematic variation of six values each for C/D ratio and system lag, and two levels of exponential function for each combination of ratio and lag. The table indicates that each rate was obtained in the same manner as in Expt. I. Since the response of the display to a control input was an angular rotation rather than a vertical displacement, the ratio expression of .5:1 should be read as $\frac{1}{2}^{\circ}$ control input produced 1° display rotation at the end of 1 sec. (1.59° final position), 1° produced a 2° rotation, $1\frac{1}{2}^{\circ}$ produced 3° rotation, and so on. The largest C/D ratio of .5:1 required a control input of 10° to compensate for the maximum deflection of 30° produced by the cam, whereas the smallest ratio of .5:9 required only 2° of control input to null out the maximum error.

The transition from a reference control input of 1° in Expt. I to one of $\frac{1}{2}^{\circ}$ ($.5^{\circ}$) in Expt. II was brought about by the limited angular displacement of the control in the left-right dimension. Since the displacement amounted to $\pm 10^{\circ}$ at the fulcrum it was necessary to adopt a reference input which would provide the necessary compensating voltage required by the larger C/D ratios.

PROCEDURE:

The order in which the twenty-four experimental conditions were presented in each experiment is given in Table 1. The number within each square denotes the condition which was presented on that particular trial, and the position of the square within a row denotes the trial number when

counting from the left. Each of the conditions followed and preceded every other condition only once in the entire series*.

Each S experienced the entire series of twenty-four conditions in a single session, but the presentation order of the conditions was different from S to S. Before beginning a session the S was allowed to manipulate the control for approximately 3 minutes in order to familiarize himself with the response relationships of the display to various control inputs.
A session consisted of a single trial on each of the twenty-four conditions. Each trial was 75 secs. in length with only the last 60 secs. recorded for purposes of analysis. The first 15 secs. was utilized by the S to get the "feel" of the control with each new condition and, in addition, it provided a method of insuring the S's inclusion and active participation in the tracking loop at the very beginning of the recorded period. There was a 25-sec. rest interval between each trial in addition to the 15-sec. pre-trial warm-up period.

The arrangement of the tracking equipment is illustrated in Figure 3. Precautions were taken to provide glare-free illumination in an environment which was relatively free of distracting auditory stimuli. Prior to the commencement of each trial the S was given a verbal signal of "ready" to prepare him for the onset of the next condition. At the end of the first

* This design allows the distribution of order and practice effects across the entire series of twenty-four conditions, but it does not allow a separation of practice effects from condition effects. However, in view of the purpose of the investigations it was considered to be appropriate. If learning occurred to such an extent that it canceled or nullified the condition effects, then the selection of proper C/D values and/or time lags was questionable or the effect upon performance produced by variation of these values was non-existent or small in extent.

15 secs. of each trial the E would reset the timer and activate the recorder. The 25-sec. interval between each trial was utilized by the S as a rest period during which the E made the necessary apparatus adjustments required by the next trial.

The interval between the two experiments was approximately one month.

RESULTS AND DISCUSSION

The results of the two experiments are presented in Figures 4-7. The group root-mean-square (RMS) scores are presented in Figures 4 and 6. Each point on the four performance curves in the two figures represents the average RMS value across the twenty-four subjects. The RMS for a given subject on a given condition over the trial period of 1 min. was obtained from the Sanborn record by measuring and squaring deviations from an assumed standard of zero at ½ sec. intervals. Therefore, each average RMS value as plotted represents the product of 24 by 120 or 2880 individual measurements.

Figures 5 and 7 depict the S's performance in terms of the mean constant error (CE). It is apparent that there was a consistent bias in the positive direction in Expt. I, indicating that the S's "pitch" error was above the reference more than below. In Expt. II the positive bias was represented as a "roll" error to the right or in a clockwise direction. Analysis of the disturbing function indicated that the number of display deflections above the reference line and in a clockwise direction exceeded those below the reference and in a counter-clockwise direction, thus explaining in part the bias which was observed.

The CE curves should be examined in conjunction with the RMS curves in order to avoid an erroneous interpretation. Viewed by themselves the CE curves would imply that the best condition in terms of performance was an average rate of 6 in/sec. in Expt. I, but when compared with the RMS curves it is observed that S variance was maximum on this condition, particularly with the unstable or positively accelerated function. The fact that there was no observable bias on this condition in conjunction with the measured RMS value indicates that the Ss had only marginal control of the system and were operating at a level of randomness which, by and large, would preclude a systematic bias.

Since the same trends and relative levels of performance are exhibited in the RMS data of both experiments the following analysis of the results may be assumed to be applicable to each. The two performance curves for the negatively accelerated (stable) function in Figures 4 and 6 clearly demonstrate the validity of the hypothesis that in a tracking situation one of the facters which determine performance is the rate of movement of the display index in response to a control input rather than the values of the C/D ratio and system lag which interact to produce it. Although each rate along the abscissa of the two figures was obtained in two different ways the RMS curves indicate that the Ss performed at the same level regardless of how a given rate-of-movement was produced. The fact that these two curves are practically coincident in both figures lends support to the principles discussed in the Introduction. Increasing the rate-of-movement of the display by decreasing the time-constant in one instance, and decreasing the C/D ratio (increasing the control "gain") in the other apparently

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Figure 4

MEAN RMS PERFORMANCE DATA FOR EACH AVERAGE RATE - EXPERIMENT I

CONSTANT LAG (STABLE CONDITION)
CONSTANT DISPLACEMENT (STABLE CONDITION)
CONSTANT LAG (UNSTABLE CONDITION)
CONSTANT DISPLACEMENT (UNSTABLE CONDITION)

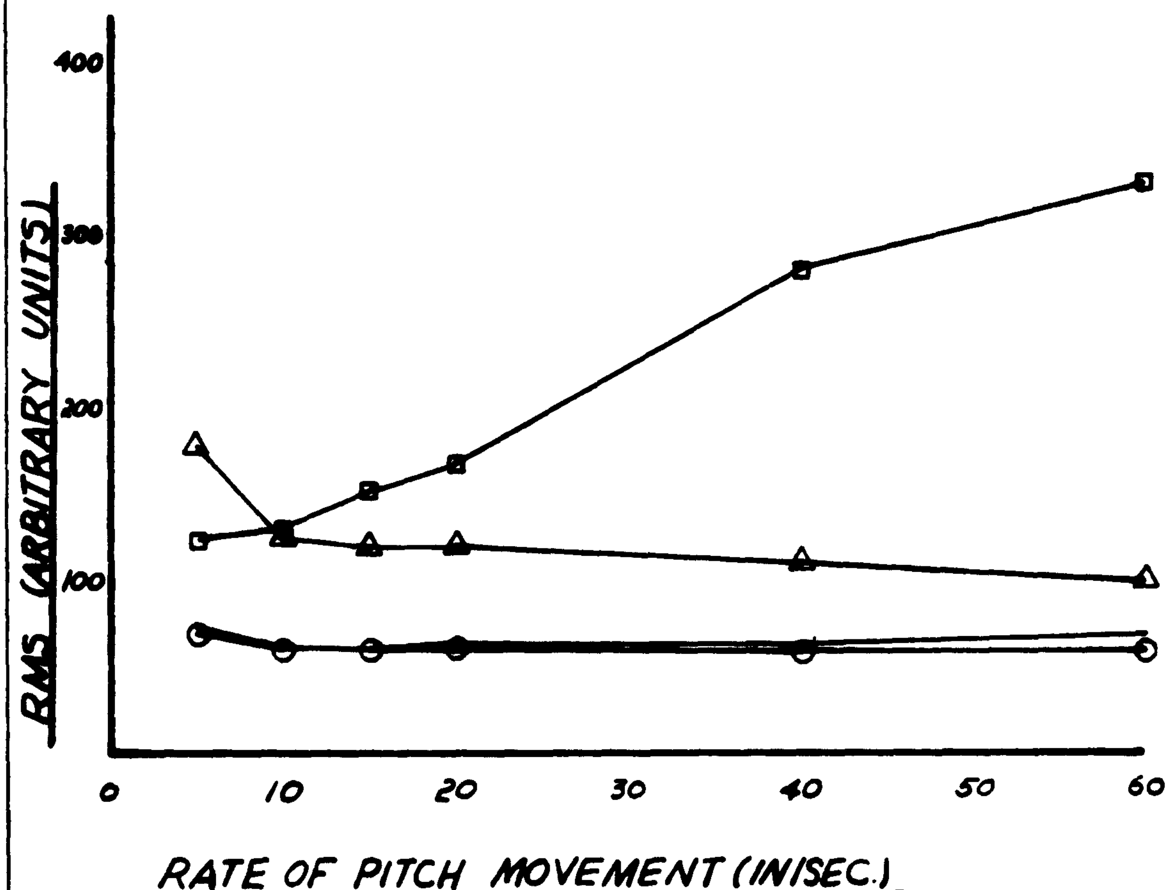


Figure 5
MEAN CONSTANT ERROR FOR EXPERIMENT I

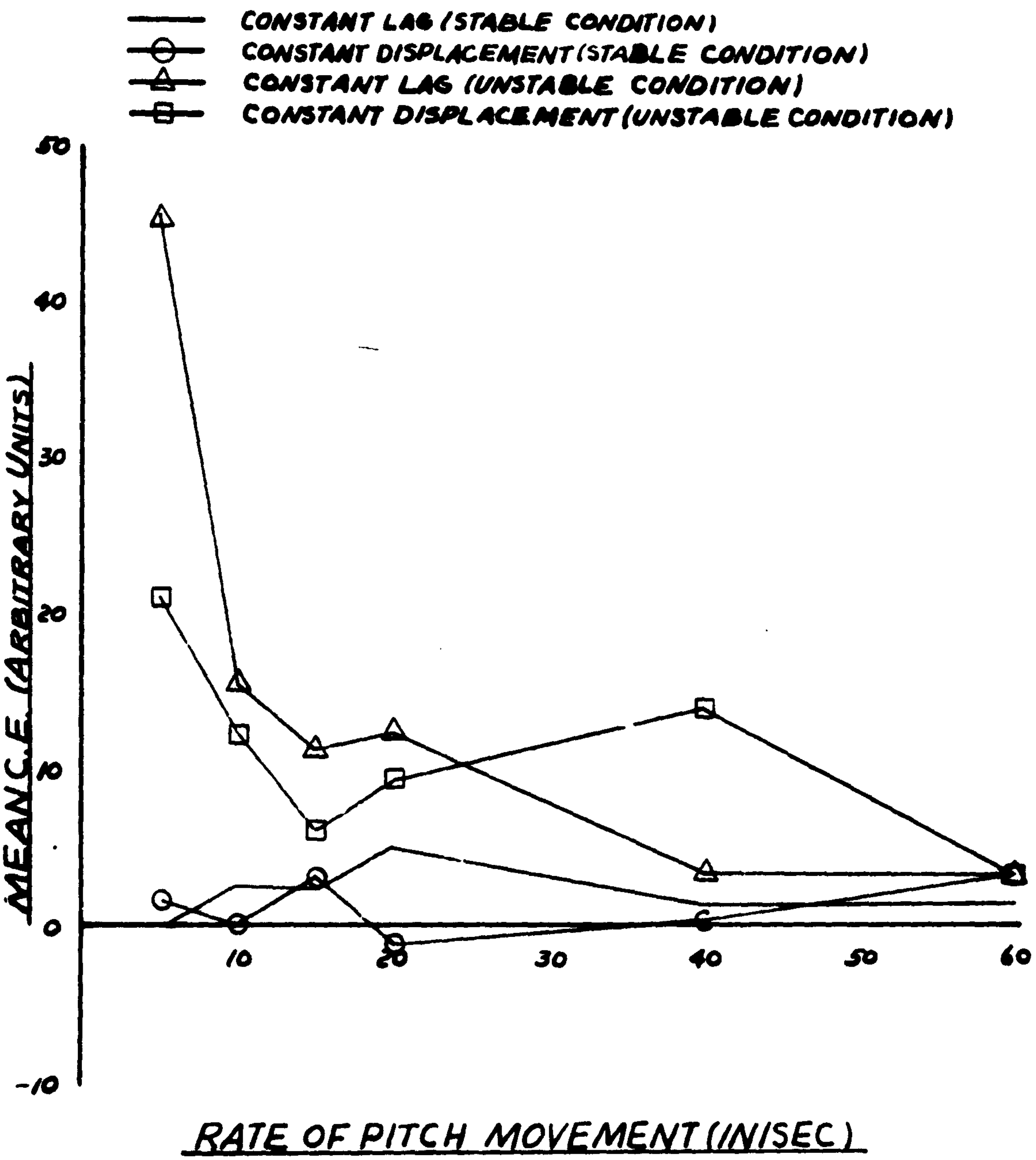


Figure 6

MEAN RMS PERFORMANCE DATA FOR EACH AVERAGE RATE ~ EXPERIMENT II

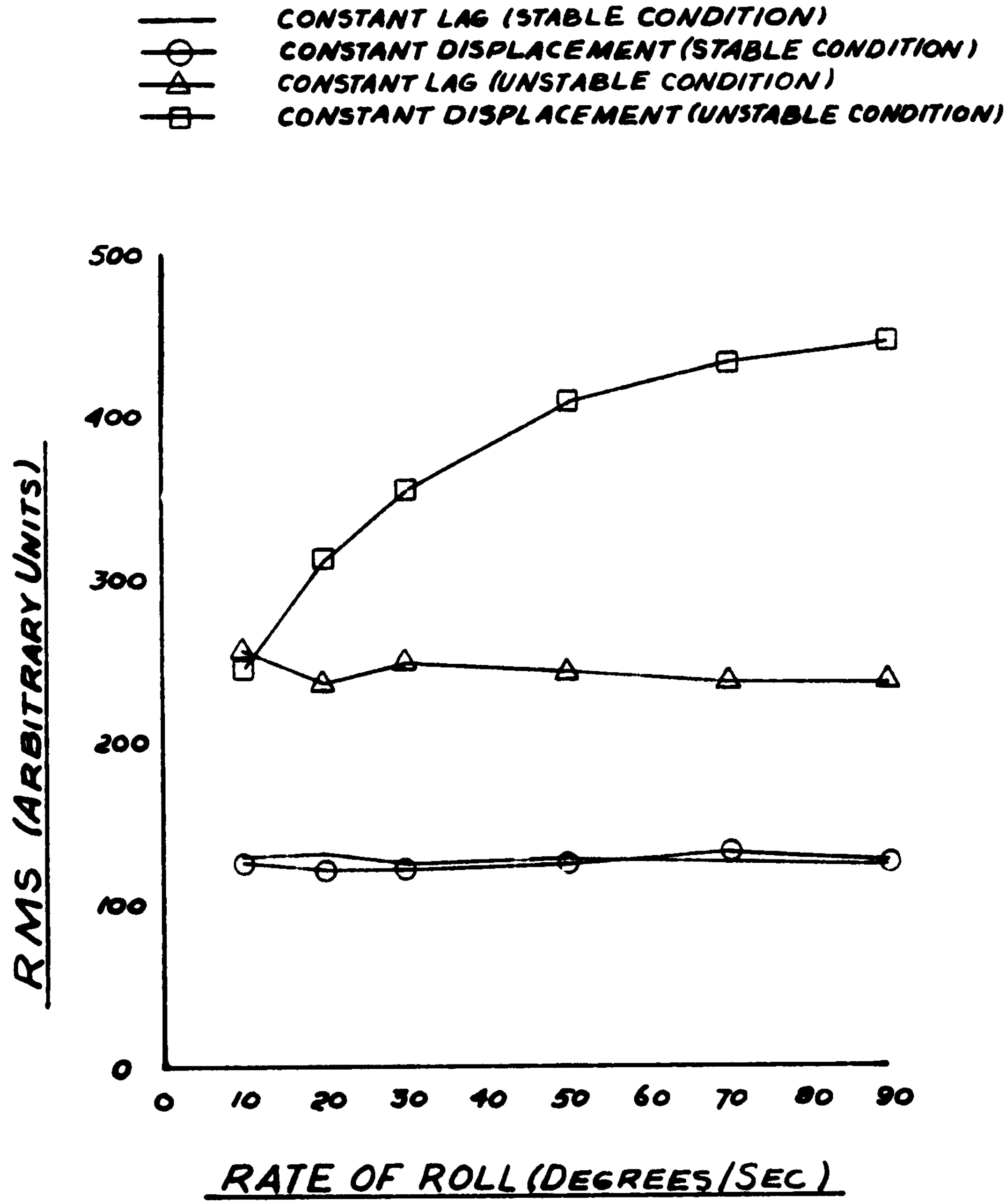
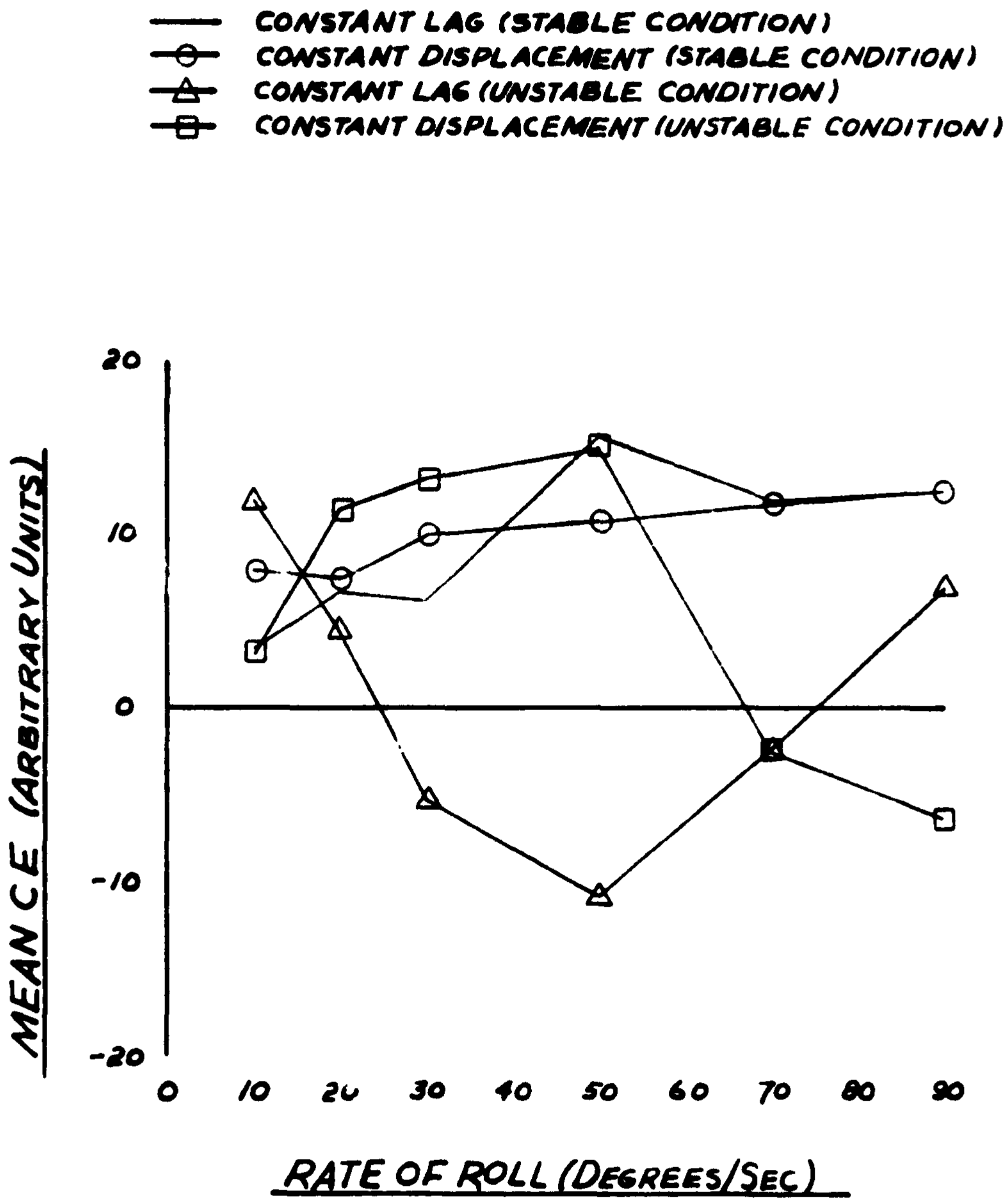


Figure 7
MEAN CONSTANT ERROR FOR EXPERIMENT II



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was not responded to differentially.

The RMS performance curves for the unstable function in Figures 4 and 6 presents an entirely different picture. Increasing the rate of display movement by <u>decreasing</u> the time delay and holding the C/D ratio constant produced a progressive deterioration in performance. Stated differently, an <u>increase</u> in the delay produced an <u>improvement</u> in performance up to an undetermined limit. On the other hand, increasing the rate of movement by decreasing the C/D ratio (increasing control "gain") and holding the time-delay constant produced a progressive increase in the level of performance in increments less than that obtained by increasing the system delay.

The fact that the performance levels for the unstable functions are coincident at a rate of 1 inch/sec. in Figure 4 and at 1°/sec. in Figure 6 is a true test of the system in that these rates were obtained with identical circuitry values within each experiment. The reliability of the system would have been seriously questioned if the Ss had performed differentially on this condition in either of the experiments. Similar performance levels at this point also indicate that the planned order of presentation served to distribute learning effects in the manner anticipated.

The use of the expressions "stable" and "unstable" functions as related to the types of response of the system requires additional explanation as to the meaning intended. The stability of a system, which refers to the response of a mass to a disturbance, is usually divided into two separate classes, static and dynamic. Positive static stability is exhibited when a body returns to its original position following a disturbance. If it does so through progressively decreasing oscillatory amplitudes it is said to

exhibit positive dynamic stability as well. On the other hand, a body which does not return or pass through its original position is conceived as being statically unstable. If it passes through the original position with progressively increasing amplitudes of oscillation it is termed as being statically stable but dynamically unstable.

Consequently, the "stable" function as used in these investigations may be characterized as being both statically and dynamically stable. Conceptually, this is essentially a position-type system in that the display member assumes a new position following a control input or disturbing signal and does not return to its initial state until the input is removed. The fact that it does assume a new position by means of negligible or highly damped progressively decreasing oscillatory behavior makes it dynamically stable.

The "unstable" function used in the experiments was both statically and dynamically unstable in that the display member responded to a control input in a positively accelerated fashion, thereby precluding its assumption of a new position or return to some initial position without the reception of additional information from the control.

Since the displacement of a body (the display member in this instance) from one position to another occurs in time, one way of expressing the relationship between the displacement distance and the time required for the displacement is in terms of the first derivative of position, the rate of movement. This is, in effect, another way of viewing the relationship that exists between the C/D ratio and the time delay of a given control system. To continue the analogy the displacement that a display member

undergoes in response to a control input is a function of the C/D ratio (control "gain") that is obtained, and the time required for the desired displacement to be achieved is determined by the lag in the system, either inherent or designed.

Although Rockway's results (Fig. 1) were not plotted in terms of rate-of-movement he demonstrated that C/D ratio (gear-type) and time-delay (exponential) do interact to influence tracking performance. When the argument put forth in the above discussion is applied (Fig. 2) in a replot of Rockway's data it would appear that his data, at least, is explicable in terms of the rate-of-movement of the display rather than in terms of the C/D ratio and time-delay per se. If the operator responds to a rate-of-movement then a given rate, whether obtained by a combination of a small C/D ratio (high gain) and long time-delay or a large C/D ratio (low gain) and short delay, should be responded to by equivalent levels of tracking performance. It is well recognised that the instantaneous rate for two such combinations could be widely disparate, but the average rate-of-movement would be equivalent in that in both instances the display would be displaced through some distance within an interval appropriate to the condition.

When the data (Figs. 4 & 6) are examined within the framework of the above analysis it is seen that the Ss performance on a given rate was not affected by a change in C/D ratio provided that it was accompanied by a change in time-delay in the appropriate direction, and conversely. The results indicate that these variations were ineffective only for those conditions in which a stable response was utilized. Aside from an insignifi-

cant improvement in performance between the values of .5 in/sec. and 1.0 in/sec. (Fig. 4) it is also noted that the Ss did not perform differentially on any of the conditions in which the display exhibited a stable response. As has been pointed out in the Introduction, even the most unsophisticated and intuitive analysis would lead to the deduction that if the rate-of-movement of a display determines the level of tracking performance then there should be some values which are too fast to be tracked efficiently and some which are too slow. If such is the case it is apparent that these conditions were not contained within the confines of the experiments. Since the selection of the various lags and C/D ratios was determined by the various rates which were chosen for investigation it is improbable that plotting the performance scores against rate-of-movement biases the observations that might be made.

It is apparent that the Ss responded to the unstable functions in a manner wholly different from that exhibited by the data for the stable functions. Here it is seen that performance was affected by the manner in which a given rate-of-movement was obtained as well as by the value of the rate itself. An increase in the rate-of-movement produced by a decrease in the C/D ratio (increase in control "gain") was accompanied by a progressive improvement in performance. On the other hand when the rate was increased by decreasing the time-constant there was a progressive deterioration of performance. An interesting feature of these curves in Figure 4 lies in the fact that they cross at a rate of 1 in/sec. and the relative performance levels are reversed beyond this point. The fact that these two curves are so widely disparate is evidence in itself that

rate-of-movement was not the determining factor or the achievement of equivalent rates with different combinations of C/D ratio and lag was not realized. In regard to the latter it was recognized that it is not feasible to ascribe a time-lag to a system which accelerates positively with time (i.e., exhibits an unstable response) in response to a control input. However, in order to reference the stable and unstable conditions to a common base (i.e., rate-of-movement) it was necessary to utilize temporal values which, theoretically, could be called time-delays. The time-delays were equivalent across the two systems only in that a step input of the control, with a given C/D ratio, would provide the same displacement of the display within the same time interval. By way of illustration a graphical representation of two such systems would show that the stable or negatively accelerated function would become asymptotic with time, whereas the unstable or positively accelerated function would continue to accelerate with time. The rationale for this approach, however, lies in the assumption that an operator does not allow an error to become asymptotic before attempting to correct it, but, instead, initiates the corrective process at the time that an error and its direction is detected. Aside from questions concerning the validity of this assumption and the circumstances under which it was utilized the important feature of these data resides in the performance trends which are noted. It would appear that decreasing the delay in a system that exhibits an unstable response creates a situation in which performance deteriorates as the system responds more quickly. However, the curves also show that increasing the immediacy with which control results are made available to the operator enhances performance

when done so by decreasing the C/D ratio and thereby increasing the rate-of-movement. When referenced to a step input of the control it is seen that the function describing the time-displacement relationship is such that an increase in control "gain" provides a more immediate response of the display and a corresponding improvement in performance. Yet, when the response of the display was increased by decreasing the time-constant operator performance deteriorated accordingly. Intuitively it would appear that increasing the rate-of-movement in this manner provided progressively less time in which the operater could correct an error before the system became completely unstable.

SUMMARY

Twenty-four Ss performed a one-dimensional compensatory tracking task in each of two experiments. Experiment I consisted of the systematic variation of three variables of C/D ratio, system-lag and exponential function while the Ss controlled for vertical (pitch) deviations of the display. Experiment II consisted of the variation of the same three variables while the Ss controlled for angular (roll) excursions of the display.

By way of observation the performance curves for those conditions in which the display exhibited a stable response indicate that a given average rate-of-movement elicited equivalent performance levels regardless of the variation utilized to obtain it. However, when the display exhibited an unstable response the operators responded differentially to a given rate. In this case the level of performance was enhanced by increases in control "gain", and deteriorated by decreases in system-lag.

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